

## TEKTITES AND THE MOON

John A. O'Keefe

Theoretical Division, Goddard Space Flight Center  
National Aeronautics and Space Administration

Tektites are small glassy objects with sizes of the order of an inch, and colored usually black and sometimes green or brown. They are found on the surface of the earth in several estimated areas which are called strewn fields. The Indomalaysian strewn field covers most of Southeast Asia from Siam to the Philippines and from South China to Java. The Australian strewn field covers the south portion of Australia and the island of Tasmania; a third strewn field covers Texas and perhaps also Georgia; a fourth strewn field covers a narrow strip of Czechoslovakia, and the fifth is a small portion of the Ivory coast in Africa.

In all these areas tektites are found to consist of a remarkably homogeneous glass containing very few inclusions. The composition of the glass is generally like that of a granite; but the difference is in having more lime and magnesia on the one hand and less soda and potash on the other. The differences are not very great, however, and by changing about 5% of the constituents it would be possible to modify a typical granite to resemble a typical tektite. Wherever tektites are found, their composition is independent of the surface conditions. For example, in the very large limestone plain of Australia, where no other rocks high in silica are known, tektites are very abundant.

In 1897, the Dutch mineralogist, Verbeek, drew attention to the difference between European tektites, which are called moldavites, and other minerals of Czechoslovakia. He suggested that the moldavites had arrived at the surface of the earth as a result of a volcanic eruption on the moon. In 1898, the great German mineralogist F. E. Seuss examined the moldavites from Europe and compared them with Australia and Indomalaysian glasses; he gave them the name of tektites (which means "melted"). Seuss considered that tektites were probably of extra-terrestrial origin like meteorites. In this finding he was influenced both by peculiarities of the chemical composition and by the external structure. Most tektites show a set of curious sculptures on the surface which resemble the marks in worm-eaten wood. The australites, in addition, show on one side, usually assumed as the front side, another set of forms which will resemble those which might be expected for a spherical body which has been melted on the front surface by passage at high speed through the air.

In the United States, G. P. Merrill, at the Smithsonian, treated some obsidians with dilute hydrofluoric acid and obtained patterns which he felt resembled those on many tektites, though this evidence was not accepted by Suess and his followers.

Several investigators proposed the possibility that the tektites were of artificial origin. This possibility was effectually disposed of during the period 1910-1920 by Suess, Michel, and others who showed that the melting point of tektites were much higher than those of artificial glass and the compositions different. In addition, no evidence has ever been uncovered associating tektites with the glass making industries. During the 1920's the New Zealand investigator H. Hardcastle and the Czechoslovakian investigator Frantisek Hanus suggested that the characteristic forms of the tektites were due to a process which Öpik calls spraying. They suggested that tektites had been formed from meteoritic bodies as the result of melting at the surface. The melted material was swept off in the form of drops by the air blast in passage through the atmosphere. Spraying theories have contributed significantly to our present views of the problem.

About 1933, in a series of papers in NATURE, L. J. Spencer compared tektites with the rock produced by impact from large meteor craters. In the meteor craters at Wabar and Henbury, Spencer discovered a large number of tiny metallic spherules. These were clearly fragments of the impact meteorite. Spencer found a few opaque reflecting bodies in tektites and suggested, correctly, as E. C. T. Chao has since shown, that these were also composed of nickel-iron. From this Spencer was led to suppose that tektites were produced in the same way as the impactites, that is, as the splash material from terrestrial meteor craters. He was further influenced by the fact that some of the bodies from terrestrial craters had a drop-like form and had evidently been liquid.

Spencer's suggestion was vigorously attacked by C. Fenner, the great Australian student of tektite forms. Fenner pointed out that the impactites from terrestrial meteor craters are nearly always slaggy; that is, they nearly always obtain a large number of bubbles and a lot of inclusions. In form, moreover, they are not really like most tektites, and they bear no resemblance whatever to the characteristic forms of the australites (as Australian tektites are called). Fenner strongly supported the spraying views of Hardcastle; he was aware, however, of two important difficulties of this theory. In the first place, it had been pointed out by Fletcher Watson that a typical meteor plunging through the atmosphere has not time to melt a substantial portion of its substance. The difficulty, as shown by Watson, is that in this brief time the heat cannot penetrate the interior even of a body of a few cm. in diameter. In the same way, Öpik's

theory indicated that a meteor passing through the atmosphere would not ordinarily be seriously melted. The heating would be so intense and so brief that the inner portion of the material would remain cold while the outer part would be vaporized; the liquid layer between would be so thin that it could not run. As a solution to these difficulties, or some of them, Fenner drew attention to a suggestion of Lincoln La Paz, namely that tektites might have originated from a shower of meteorites similar to the great Canadian fireball procession of February 9, 1913, for which the name Cyrillid has been proposed.

The Cyrillid shower, unlike all other meteor showers known to me, consisted of a long procession of bodies passing over the same course in the sky, taking several minutes to pass a given point. It was observed over an area extending from Mortlach, near Regina, Saskatchewan, to a point in the South Atlantic off the coast of Brazil. The original investigator, C. A. Chant, who had data only from Canada and Bermuda (plus two observations in the United States), courageously asserted that the Cyrillids had been in orbit around the earth before their fall. Since Chant's pioneer paper, evidence uncovered by W. F. Denning, W. H. Pickering, and A. D. Mebane have confirmed Chant's theory by filling the gaps and extended the line. It has also been shown that these bodies were not observable except along the arc of the great circle first outlined by Chant. Fenner pointed out that from a very extensive shower of this kind which was nevertheless not world-wide, it would be possible to explain the size of tektite strewn fields. He also perceived, I think, though his paper is not quite clear, that in the velocities of the Cyrillids he had a clue to the problem of melting.

In 1940, in two papers in SKY AND TELESCOPE, H. H. Nininger proposed to combine the impact theory of Spencer with the theories of extra-terrestrial origin by suggesting that tektites originate from meteoritic impact on the moon. In 1954, G. P. Kuiper, after a study of the moon's surface features, concluded that some of them could be reasonably explained by the hypotheses that the chemistry was related to that of tektites.

About the same time, H. C. Urey pointed out an extremely serious difficulty in the hypotheses of extra-terrestrial origin of tektites, namely, the problem of the manner in which a swarm of bodies coming through space could be held together. He pointed out that a swarm as large as the continent of Australia would have to be so dense that it would pile the tektites up knee deep over the continent, if it were sufficiently dense to resist perturbations by the sun. He therefore returned to the impact suggestion of Spencer with the modification that he assumed a comet as the impact body instead of a meteorite in order to avoid the difficulty that it is hard to find associated craters.

During the past few years considerable progress has been made on the problem by J. H. Reynolds in California and Gentner and Zähringer in Germany who have demonstrated that the tektites fall into three age groups: the U. S. tektites which are about 30 million years old, the European tektites which are about 8 million years old, and the Australian and Indomaysianites which are about 600,000 years old, as judged by the amount of argon 40 which has been formed from potassium 40 in tektite interiors since they were last strongly heated. H. Friedman at the Bureau of Standards has shown by accurate analytical methods what had been surmised many times before, namely that the tektites are extraordinarily dry. They contain, he finds, from 20 to 1500 parts per million of water. This is lower than any ordinary terrestrial rock. In 1958 C. M. Varsavsky, T. Gold, and J. A. O'Keefe, revised the theories on origin from the moon. O'Keefe in particular returned to the suggestions of La Paz and Fenner that the arrival had taken place after the manner of the Cyrillids. In 1960 O'Keefe compared the theories of Öpik for meteor ablation with tektite forms. He showed that at least an approximate agreement can be obtained between the form and size of tektites on the one hand and the drops which would be formed by the spraying idea of Hanus and Hardcastle on the other, provided that the parent body moved through the atmosphere in a path comparable with the Cyrillid shower. In the same year, D. R. Chapman, working closely with George Baker of CSIRO in Australia, published the results of a precise analysis of the australites which showed that they could be explained as formed from solid bodies entering the atmosphere cold and traveling along trajectories nearly parallel to the surface of the earth. Chapman's work provided physical underpinning to a set of ideas put out in 1944 by Baker, on the aerodynamic control of australite forms. The ablation theories which Chapman used have been tested so thoroughly in conjunction with re-entry problems for astronauts and military warheads that he was able to calculate the entry velocity and angles with surprising precision. These indicate a trajectory very considerably more eccentric than the Cyrillid orbit; they suggest a direct approach from the moon. Also in 1960, the USGS mineralogists E. C. T. Chao and E. Shoemaker, investigated the debris around Meteor Crater. For the first time they found, in a natural source, the silica mineral coesite, which is formed only at very high pressures. There is every reason, from the physical properties of coesite, to believe that near the surface of the earth it can only be formed as the result of meteoritic impact. Hence, when coesite was discovered in August of 1960 in the enormous Ries basin in central Germany, this amounted to a convincing demonstration that the Ries is, as some observers had long expected, a meteor crater. It is now possible to set the tektites alongside the debris from a typical meteor crater and to compare the structure and mineral composition. This work is now going on at the USGS, and the results will be awaited with great interest.

At the present time, it appears to be most likely that tektites originate as the result of meteoritic impact. Chao has shown that the spherules which Spencer detected are actually composed of nickel-iron, and this is practically the trade mark of meteoritic origin. The differences in composition and particularly in water content between tektites and terrestrial rocks point to some other body than the earth. The resemblances in chemical composition suggest something closely allied. Just from the nearness of the moon we would expect that its debris should reach the earth more often than that from any other body. In particular, Eugene Shoemaker at USGS has shown that in an ordinary meteoritic impact some debris should be thrown from the moon to leave it forever.

The biggest problem is to account for the debris which will have been thrown from the moon but will not have gone into a grazing orbit around the earth. This material cannot be converted into tektites. From what is known of the physical structure of the moon's surface it appears unlikely that the tektites can exist on the moon in that form. It therefore appears possible that the majority of lunar debris which reaches the earth goes unrecognized. The chemical composition is as has been noted, rather ordinary; and if it were not for the glassy structure, tektites would probably never attract attention. We are led to suppose then that from time to time the earth is struck by acid meteorites with a chemistry like a tektite and a porous structure of some kind. There is one rather well-authenticated case, namely the Igast object. Igast was originally classed as a meteorite; the fall, however, was very small, and a not too careful dealer who claimed to have recovered a much larger piece distributed chunks which he claimed were parts of Igast. These were later shown to be spurious. A careful investigation of the surviving genuine specimens of Igast is now under way.

If the tektites do come from the moon then we are led to a series of interesting conclusions about the moon. Since they are of a general nature of a granitic rock and have a density less than that of the moon, they must represent some sort of a product of partial fusion on the moon. That is to say, they must represent granitic lavas, acid lavas which have come to the surface of the moon as the result of a heating of the interior. Similar theories of the formation of granite on the earth have always had to contend with rival theories according to which granite is the result of the action of water on a basaltic rock. Thus, the proof that the tektites come from the moon would cast important light on one of the most controversial questions in modern geology.

In the second place, studies of the relationship of lead to uranium by G. R. Tilton and of rubidium to strontium by Pinson and Herzog

have shown that the present chemistry of the tektites was produced a few hundred million years ago. Since the age of the earth is believed to be some billions of years, the implication is that volcanic processes have been active on many parts of the moon throughout its history, and perhaps even at present. This surmise is supported by the observations of Kozyrev, who detected activity in the central peak of the lunar crater Alphonsus in 1958.

In the third place, the notion of an acid chemistry of the surface of the moon agrees not only with the pumice-like structure of the outer surface which has been surmised from thermal, optical, and polarization measurements, but also with the possible presence of small glass beads on the moon. These last are suggested by the phase effects on the lunar bright rays near full moon.

For all of these reasons, I believe, then, that in these strange and beautiful stones we have remelted portions of the surface of the moon.